Ecology Ditch: A Best Management Practice for Storm Water Runoff Mitigation

Michael E. Barber, M.ASCE[1]; Steven G. King, A.M.ASCE[2]; David R. Yonge[3]; and Wade E. Hathhorn, M.ASCE[4]

Abstract: A full-scale physical model of a modified infiltration trench was constructed to test a new storm water best management practice called an ecology ditch. The ditch was constructed using compost, sand, and gravel, and a perforated drain pipe. A series of 14 tests were conducted on the physical model. The tests controlled rainfall application and overland roadway runoff amounts and monitored outflow from the discharge pipe. The objectives were to increase the time to peak and reduce the peak discharge coming out of the pipe. The results were also used to calibrate a modified existing unsaturated two-dimensional groundwater flow code. After the code was calibrated, computer simulations were performed to determine the effects of storm size, rainfall distribution, constant rainfall application, media type, initial conditions, and the physical size of the ecology ditch. The simulations used 24-hour duration storm sizes of 0.64, 1.27, 2.54, 3.81, 5.08, and 6.35 cm (0.25 to 2.5 in.). Peak reduction was found to depend greatly on input hydrograph distribution and the ability of the soil to store water. In turn, the storage in the soil was found to be dependent on the intensities of the input hydrograph. The peak delay time for larger storms was quantifiable since it depended on the saturated hydraulic conductivity and the distance of the flow path. For larger storms, the ecology ditch managed a peak reduction in the range of 10 to 50%.

DOI: 10.1061/(ASCE)1084-0699(2003)8:3(111)

CE Database subject headings: Best management practice; Ditches; Storm runoff; Remedial action; Water infiltration.

Introduction

As urban areas continue to develop, storm water runoff problems become more severe and cost-effective options for treating the problems become more limited. Additional impervious area increases the magnitude of the hydrograph peak, the associated runoff volume, and the pollutant loading (Driscoll et al. 1990; FHA 1996). Adverse impacts include downstream flooding, channel scour, and sediment and pollutant transport. Moreover, since many state and local regulations restrict storm water discharge to predevelopment hydrograph magnitudes, additional land must be purchased for storage and detention. The collection networks and treatment systems needed to handle the larger storm water volumes and pollutants result in increased infrastructure costs. To effectively mitigate these impacts, best management practices (BMPs) such as detention ponds, swales, and infiltration galleries are used (Ellis et al. 1986; Schueler 1987; Urbonas and Stahre 1993). In urban areas, land required for treatment facilities can be limited and costly.

An ‘‘ecology ditch’’ is a modified partial infiltration trench designed for the purposes of reducing and attenuating peak discharges and removing pollutants associated with urban storm water runoff. A typical infiltration trench allows storm water to be temporarily stored in the porous media backfill. Dewatering of the trench occurs through deep infiltration (Harrington 1989; Duchene et al. 1994). By contrast, when storage capacity is exceeded, an ecology ditch is drained via a perforated pipe located near the bottom of the trench similar to the design initially proposed by Urbonas and Stahre (1993). The drain pipe provides the benefit of removing water from the trench when deep infiltration is too slow or not desirable. As illustrated in Fig. 1, the trench backfill consists of sand and compost layers that retain a portion of the infiltrated storm water for plant uptake and evaporation. It is the increased affinity for pollutants and the additional potential for evapotranspiration storage afforded by the compost that makes this unique from other infiltration BMPs. Extended wings also increase infiltration surface areas yielding better hydraulic treatment of the hydrograph. It is also anticipated that the vegetation will facilitate nutrient removal and trap metals adsorbed to sediments as has been demonstrated in BMPs such as swales and grass strips (Harper et al. 1984; Hewitt and Rahed 1992; Newberry and Yonge 1996). In a related study by Koob and Barber (1999), the organic carbon contained in the compost provided adsorption and filtration sites for pollutants such as metals, polynuclear aromatic hydrocarbons, and sediments. Furthermore, since most ecology ditch applications use areas within existing right-of-ways, cost savings may be realized in property acquisition.

[1]Director, State of Washington Water Research Center and Associate Professor, Dept. of Civil and Environmental Engineering, Washington State Univ., Pullman, WA 99164-3002. E-mail: meb@wsu.edu

[2]Assistant City Engineer, City of Wenatchee, 25 N. Worthen St., Wenatchee, WA 98801. E-mail: sking@CityofWenatchee.com

[3]Professor, Dept. of Civil and Environmental Engineering, Washington State Univ., Pullman, WA 99164-2910. E-mail: yonge@wsu.edu

[4]President, Economic and Engineering Services, 111 SW 5th Ave., Suite 1670, Portland, OR 97204. E-mail: WHathhorn@mail.ees-1.com

Note. Discussion open until October 1, 2003. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on February 19, 1999; approved on November 15, 2002. This paper is part of the ***Journal of Hydrologic Engineering***, Vol. 8, No. 3, May 1, 2003. ©ASCE, ISSN 1084-0699/2003/3-111–122/$18.00.

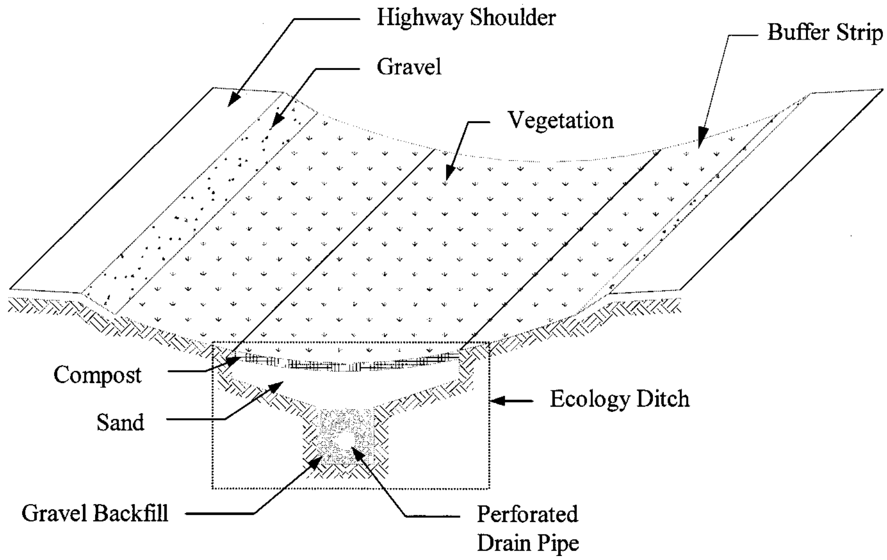

Fig. 1. Isometric of Ecology Ditch

The objectives of this study are to demonstrate the utility of the ecology ditch and provide insight into design considerations. To accomplish these objectives, a full-scale physical model was constructed in the Albrook Hydraulics Laboratory at Washington State Univ. (WSU), Pullman, Wash. The physical model was subjected to simulated rainfall/runoff events to provide the information necessary for calibration of the computer code, *Simulating Water Flow and Solute Transport in Two-Dimensional Variably Saturated Media (SWMS2D)* (Simunek et al. 1994). The computer model was used to examine the effects of different ecology ditch configurations and demonstrate the impacts of precipitation patterns on the effluent hydrograph.

Methods and Procedures

Full-Scale Model of Ecology Ditch

A physical model was constructed to represent actual field conditions while maintaining precise laboratory controls. The model included rainfall and highway runoff application systems allowing variable application rates on the ditch and highway surfaces. Three banks of nozzles provided the necessary range of flows to imitate the Soil Conservation Service (SCS) Type I-A distribution for storms ranging from 0.65 cm (0.25 in.) to 6.35 cm (2.5 in.). The 4.88 m (16 ft) long model was built on a 2% longitudinal slope. The cross-sectional dimensions of the ditch are shown in Fig. 2. Three types of media were layered in the ecology ditch. The surface media was a 10.2 cm (4 in.) thick layer of WSU compost. Underlying the compost was a clean sand layer, followed by 3/8 in. minus gravel used for pipe bedding.

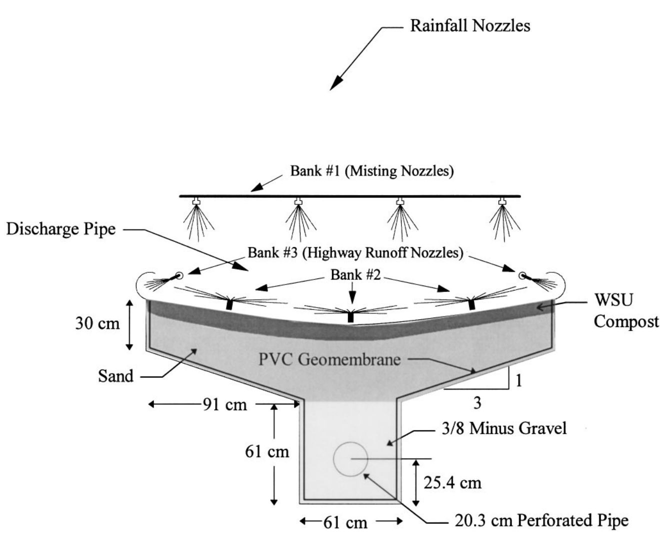

Fig. 2. Dimensions of Ecology Ditch cross section

Soil properties were determined for each media. Saturated hydraulic conductivity tests for the compost, sand and gravel yielded 0.052, 0.017, and 0.10 cm/s, respectively. As illustrated in Fig. 3, the sand and gravel hydraulic conductivity values fall well within the ranges reported in literature (Fetter 1994). Bulk densities of 1.60 and 1.61 g/cm^3 were measured for the sand and gravel, respectively. Hanging column tests were performed to determine the unsaturated van Genutchen parameters as shown in Table 1. According to the literature, the van Genutchen curve-fitting parameter m is often estimated by the equation $m = 1 - 1/n$. However, this approach is not universally accepted (Wilson et al. 1992). Sequential iteration of the m and n parameters provides an "m free" solution to the moisture release curve. Table 1 contains sets of unsaturated parameters based on both methods. For the materials used in this study, better results were obtained using the m free values. Consequently, the parameters on the left side of Table 1 were used in the computer simulations.

Physical and Numerical Modeling

As shown in Table 2, 14 experiments were performed on the physical model. These experiments tested the effects of storm size and duration on the outflow hydrograph. The storm events applied to the physical model followed the SCS Type I-A distribution. The runoff flow rate was based on precipitation falling on a pavement surface that was 3.96 m (13 ft) wide per foot length of the ecology ditch. Fig. 4 is a typical result observed during these tests. Output from these experiments allowed determination of percent peak reduction and peak delay time for all of the conditions tested. Percent peak reduction is defined by the difference in

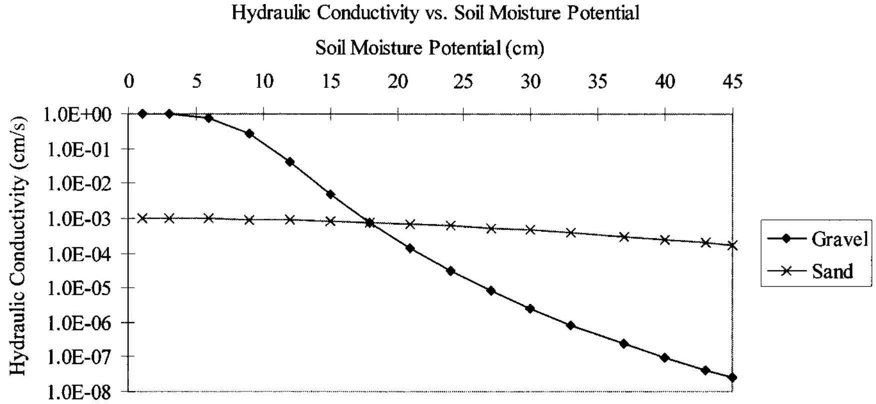

Fig. 3. Unsaturated hydraulic conductivity comparison between sand and gravel

Table 1. Soil Properties and van Genutchen Parameters

	Curve Fit with m Free					Curve Fit with $m=1-1/n$				
	θ_{sat}	θ_r	α	n	M	θ_{sat}	θ_r	α	n	m
Sand	0.35	0.065	0.106	21.04	0.06	0.35	0.070	0.071	2.91	0.65
Gravel	0.40	0.025	0.137	2.03	1.94	0.40	0.025	0.199	4.41	0.77

Table 2. Summary of Full-Scale Model Experiments

Run number	Storm size (cm)	Storm duration (h)	Description
1	5.08	24	Initial run used to work out system deficiencies
2	3.38	24	Effect of 24 h storm
3	—	—	Steady rain applied until steady state reached
4	—	—	Determine storage volume below perforated pipe
5	1.27	6	Moisture probes installed (failed); Consistency
6	1.27	6	Tensiometers installed; Consistency
7	1.27	6	Rain only applied
8	1.27	6	Highway runoff only applied
9	1.27	3	Effect of duration
10	1.27	1	Effect of duration
11	2.54	6	Effect of storm size
12	1.27	6	Chloride tracer study #1; Consistency
13	0.64	6	Effect of storm size
14	1.27	6	Chloride tracer study #2; Consistency

between the input peak and the output peak divided by the input peak. Peak delay time is simply the time between the input hydrograph peak and outflow hydrograph peak.

Subscale infiltration experiments were performed to determine the runoff infiltration behavior with respect to the side slopes of the ecology ditch and to investigate whether the runoff was traveling strictly along the bottom geomembrane. A plexiglas flume 15.24 cm (6 in.) wide by 111.76 cm (44 in.) long and 30.48 cm (12 in.) deep was filled with the same sand used in the ecology ditch. The flume was tilted to side slopes of 5 and 25% and water applied to the upper end of the flume. Fig. 5 illustrates the layout of the infiltration experiment. Measurements of wetting front propagation were recorded as a function of time. Additionally, the effects of initial sand moisture content on infiltration behavior were tested.

The subscale infiltration experiments provided crucial information with respect to the behavior of infiltrating water. The effects of wing side slopes were tested using 5 and 25% slopes. In general, the wetting front propagation along the 5% slope was shorter than the 25% slope as shown in Fig. 6. For example, at an elapsed time of 100 min, the wetting front in the 25% slope test advanced 15 cm further than the front in the 5% slope test. Increased wetting front advancement in the 25% slope test is explained by the effect of gravity. The largest impact of gravity occurs in the transmission of water behind the wetting front. Rapid wetting front propagation results from a high-potential difference across the wet-dry interface due to high-water contents just behind this interface (Hillel 1982).

A second important observation from the infiltration experiments was the size of the transmission paths resulting from infiltrated water. Three tests were performed to determine the path thicknesses. The average transmission path thickness was measured approximately 30 cm (12 in.) from the lower end of the experiment. Table 3 summarizes these measurements.

The path thicknesses vary little at the point of measurement between the three experiments. The path thickness is a direct result of capillarity. The sand used in these experiments exhibited relatively low capillarity resulting in small transmission path thicknesses. Fig. 7 illustrates an example of the transmission path thickness for both the dry and wet initial conditions for a 5% side slope. The heavy lines represent the infiltration path resulting from wet initial conditions.

The results shown in Figs. 6 and 7 illustrate the transmission paths thicknesses were relatively independent of initial conditions and side slopes. Based on these results, it can be assumed the transmission path or the stream tube remains fairly constant in size and shape. Since all of the experiments involve applying a spike or a pulse in the input hydrograph, knowledge of how a pulse propagates through the system is important. A spike or pulse of water applied to an unsaturated system dissipates as it travels

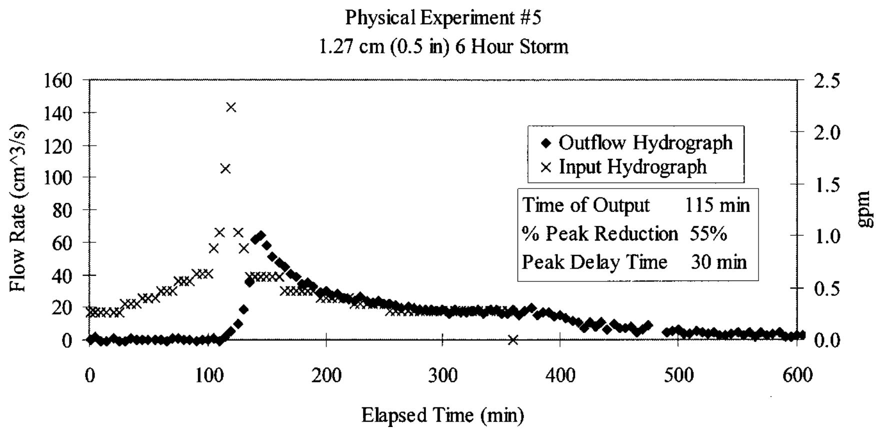

Fig. 4. Outflow hydrograph resulting from 1.27 cm (0.5 in.) 6-h storm

Table 3. Transmission Path Thickness

Experiment number	Slope (%)	Initial condition	Path thickness (cm)
1	25	Dry sand	10.5
2	5	Dry sand	11.5
3	5	Wet sand	10.0

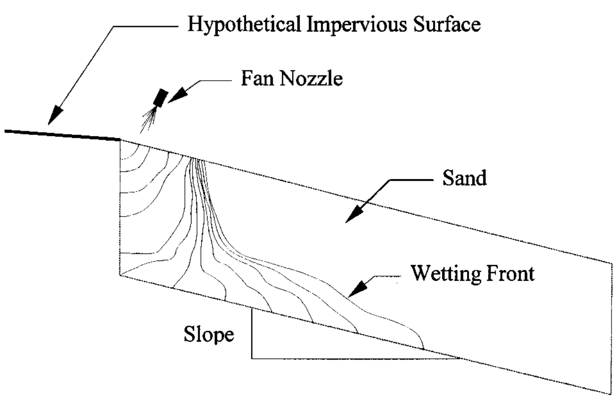

Fig. 5. Subscale infiltration experiment wetting front map

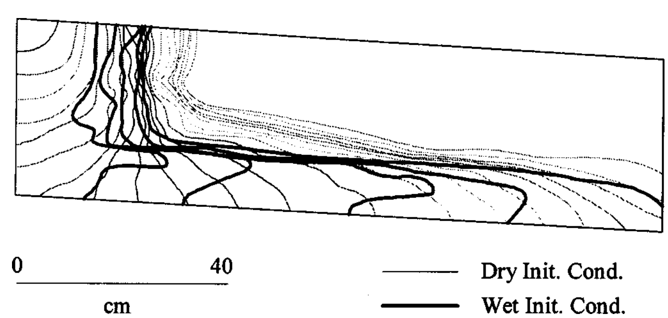

Fig. 7. Infiltration transmission paths (5% side slope)

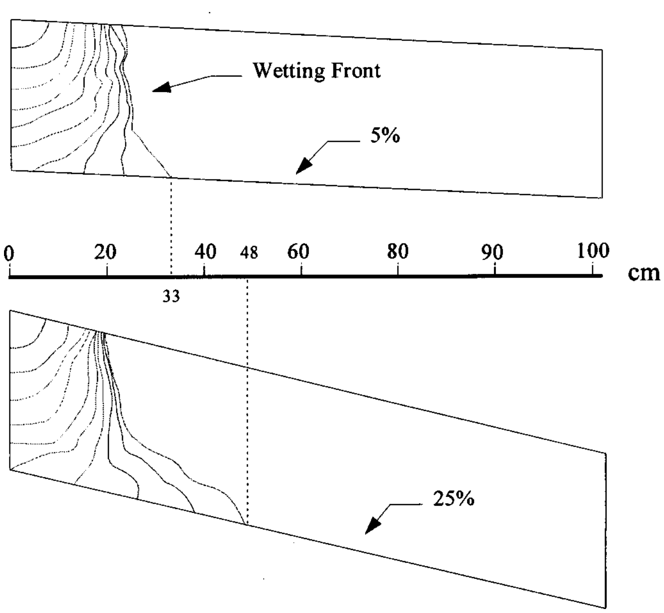

Fig. 6. Effect of slope on wetting front propagation after 100 min

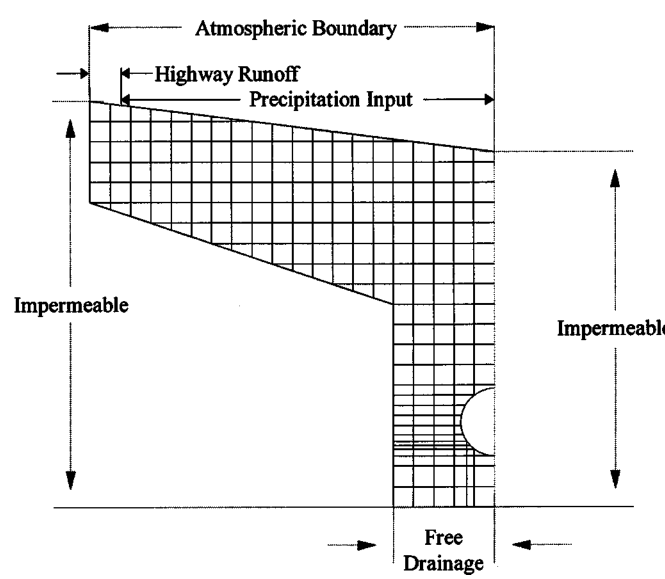

Fig. 8. Computer model mesh configuration and boundary conditions

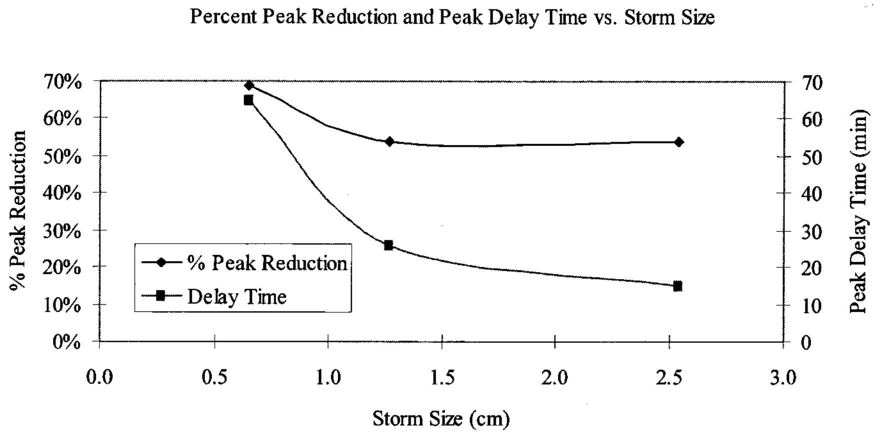

Fig. 9. Effects of storm size on peak reduction and peak delay

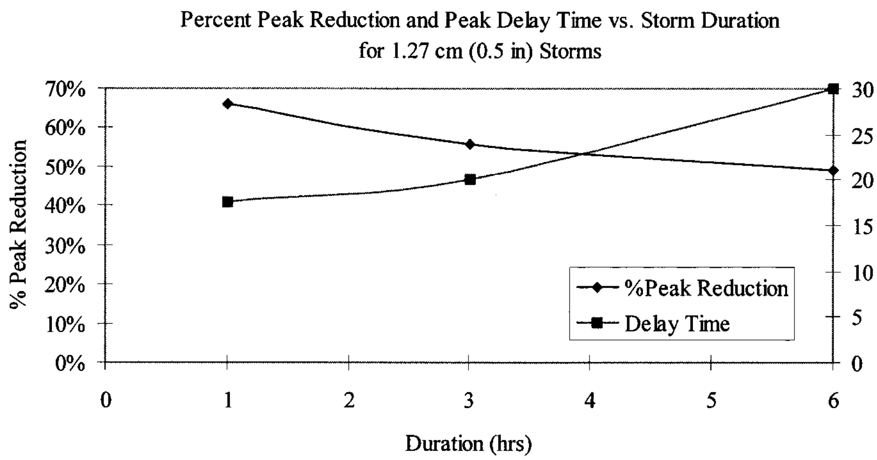

Fig. 10. Effects of storm duration on percent peak reduction

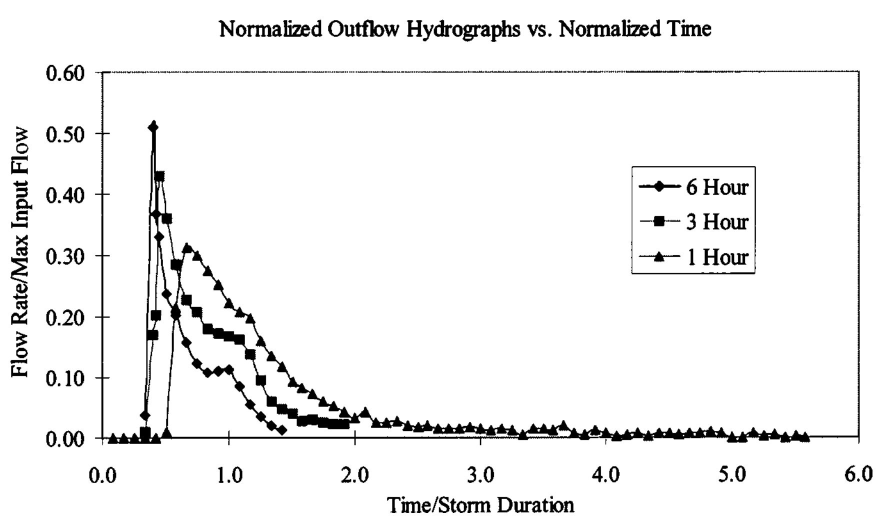

Fig. 11. Comparison of 1.27 cm (0.5 in.) storm for different durations

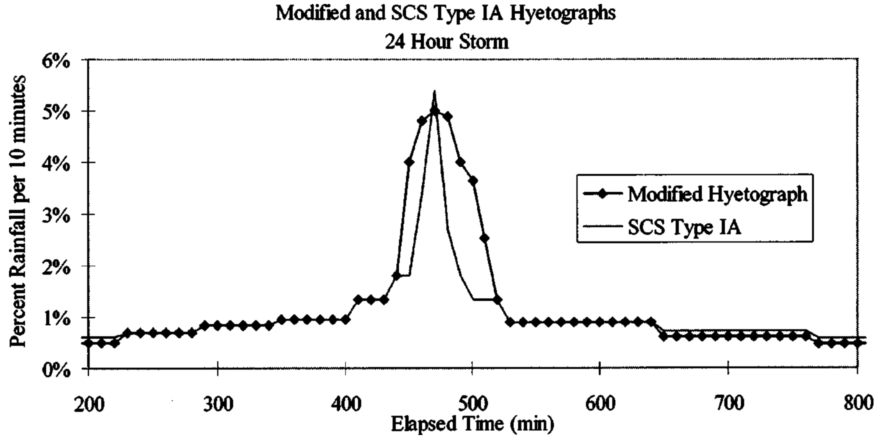

Fig. 12. SCS Type IA and modified hyetographs between 200 and 800 min

through the soil. Dissipation occurs as a result of storage in the soil matrix. The saturation or storage level increases with input intensity, causing a reduction of the peak input pulse. Dissipation also occurs due to redistribution of water in the soil matrix from the tail of the pulse (Hillel 1982). Therefore, the pulse continually decreases in intensity as it spreads through the soil matrix.

The *SWMS2D* code was applied to the ecology ditch for simulating two-dimensional (2D) vertical planar flow. The ultimate goal was to replicate results from the physical model with the code through calibration and then simulate alternative designs of the ecology ditch. An extra atmospheric boundary condition was added to *SWMS2D* to permit the application of highway runoff at the edge of ditch. With the assumption of symmetry, a half section of the ecology ditch was modeled to reduce computation time. The domain is made up of 6.1 cm×6.1 cm (0.2 ft×0.2 ft) grid elements. Grid elements can be rectangular or triangular allowing the irregular geometry shown in Fig. 8. Specified flux, unit gradient, and specified head boundary conditions make up the perimeter of the domain.

After calibration of the modified code was completed, computer simulations were performed to test the effects of storm size, rainfall distribution, constant rainfall application, media type, initial conditions, and the physical size of the ecology ditch. The simulations used 24-h duration storm sizes of 0.64, 1.27, 2.54, 3.81, 5.08, and 6.35 cm (0.25 to 2.5 in.). Another test was conducted with constant application rates of 0.06, 0.24, 0.48, and 1.20 cm/min (0.024 to 0.47 in./min). Additional simulation information can be found in King (1997). Using the results from these tests and the physical model experiments, the percent peak reduction and peak delay time were determined as a function of storm size.

Results and Discussion

The two indices of peak reduction and peak delay time are important in design. The values of their limiting performances, seen in the exponential decay as a function of storm size, provides opportunity for ease of comparisons for different conditions. These limiting values are compared in the following analysis and discussion.

Impact of Storm Size

An important trend noticed in the experiments was the effects of storm size on percent peak reduction and attenuation of the time to peak. The effects of storm size can also be equated with the effects of larger drainage areas (i.e., more highway lanes). All of the tests yielded a decrease in both the percent peak reduction and peak attenuation with increasing storm size. Fig. 9 illustrates these trends. An important characteristic can be seen in all of the experiments. The drop in percent peak reduction and peak attenu-

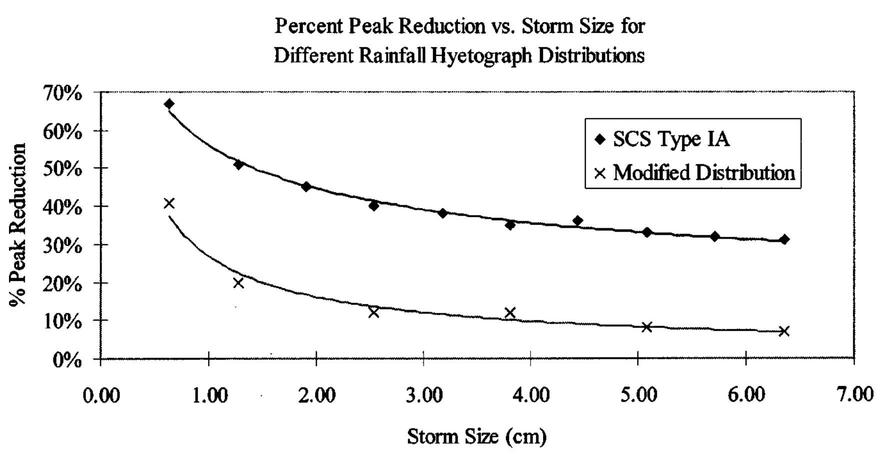

Fig. 13. Effects of input distribution on peak reduction (24-h storms)

Table 4. Results of Constant Rainfall Application

Runoff intensity/length (cm^3/s/cm)	Maximum ditch storage (cm^3)	Average transmission path water content (%)	Approximate time to steady state (s)
0.610	6.0×10^5	0.35	2,160
0.244	4.0×10^5	0.31	3,600
0.122	2.8×10^5	0.26	5,100
0.030	1.5×10^5	0.20	11,280

ation tends to flatten out at storm sizes of approximately 1.27 cm (0.5 in.) and larger. These occurrences are caused by an increase in ecology ditch soil water contents in the larger or higher intensity storms. An increase in water content results in greater storage and an increase in the hydraulic conductivity. As the percent peak reduction flattens as a function of storm size, the storage in the soil must increase for larger storm events. Once saturation is reached, the hydraulic conductivity cannot increase any more, causing the peak delay time to approach a minimum.

Effects of Storm Distribution

The impact of storm distribution was shown in two experiments testing storm duration and a modified storm input distribution. The effects of storm length were analyzed using three 1.27 cm (0.5 in.) storms with durations of 1, 3, and 6 h. All three storms used the SCS Type I-A rainfall distribution. In general, the percent peak reduction decreased with storm duration and the peak delay time increased as shown in Fig. 10.

The trend of increased peak delay time with increased duration is reasonable since the storm intensity decreases with longer storm durations. A decrease in storm intensity reduces the water content in the vicinity of the pulse and the corresponding effective hydraulic conductivity causing greater lag between peaks. Recall that unsaturated hydraulic conductivity decreases rapidly with small decreases in water content.

Notice the trend of decreased peak reduction with increasing storm duration. One would expect greater peak reduction and spreading of the hydrograph as a result of lower-effective hydraulic conductivity and soil moisture content. To help explain this occurrence, a normalized plot of the outflow hydrographs is shown in Fig. 11. The outflow hydrograph flow rates were normalized by their corresponding maximum input flow rate and the elapsed time was normalized by the storm duration.

Analyzing Fig. 11 indicates that the relative width of the normalized hydrographs decrease with increased duration. This trend shows, relative to the input storm duration, the outflow hydrograph has a greater spread with the higher intensity shorter duration storms. This spread of the hydrograph width causes greater percent peak reduction. Also, the drainage or tail of the hydrograph is most affected by duration. Upon further consideration, this occurrence can be explained fundamentally. For example, the higher-intensity 1-h storm puts a short spike on the system. The spike propagates through the system rapidly with increased water contents and corresponding hydraulic conductivities. Since the spike has a higher intensity over a short period, a wider range of water content is used as storage causing greater peak reduction. If the spike is long in duration and lower in intensity, the range of available water contents for a given peak intensity is reduced causing less peak reduction. The net result is greater temporary storage of the peak input in the soil matrix for shorter higher-intensity storms.

The impact of distribution on percent peak reduction and peak delay time was further tested by comparing results generated by the SCS Type I-A distribution to those from a modified distribution. The modified distribution is wider in the area of the peak as shown in Fig. 12. The reoccurring trend of peak reduction approaching a minimum value with increasing storm size is evident in Fig. 13. However, the value of the minimum reduction is highly related to the shape of the input hydrograph for a given ditch media. Fig. 13 illustrates this relationship in a comparison of percent peak reduction resulting from the SCS Type I-A and the modified rainfall distributions.

The impact of the input hydrograph shape may have the single largest effect on the efficiency of the ecology ditch to attenuate the peak flow. Notice, Fig. 13 shows a 23% drop in the minimum peak reduction for the modified distribution. The modified hyetograph applied relatively high-intensity rainfall for 60 min versus 30 min associated with the SCS Type I-A hyetograph. This extended period of high-intensity input caused the drastic decrease in the percent peak reduction.

As the applied peak duration increases, the moisture content in the transmission path approaches the steady-state water content for a given peak intensity. The steady-state water content along the liner is dependent on the storm intensity. Theoretically, if

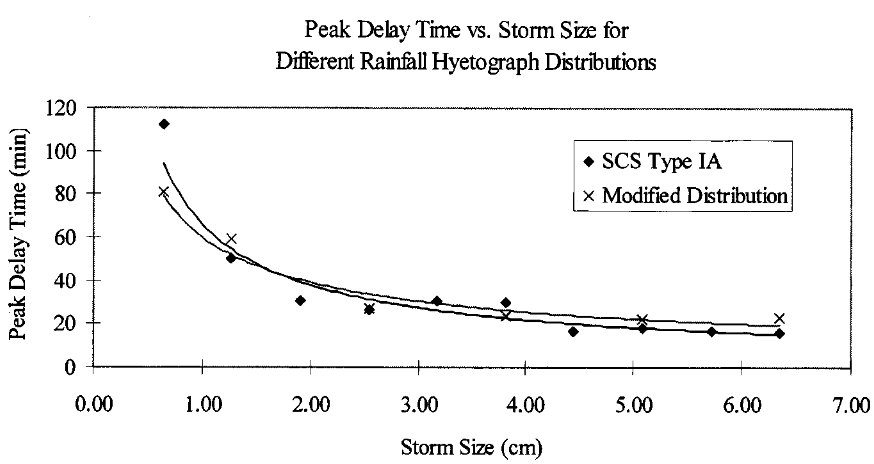

Fig. 14. Effects of input distribution on peak delay time (24-h storms)

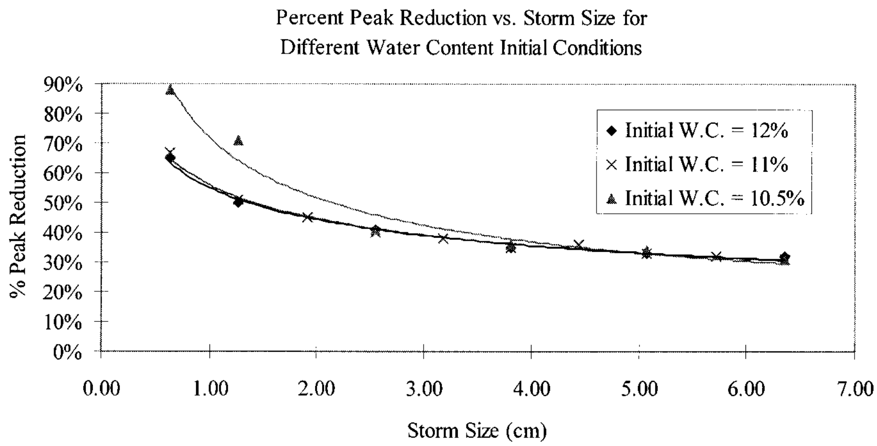

Fig. 15. Effects of initial conditions on peak reduction (24-h storms)

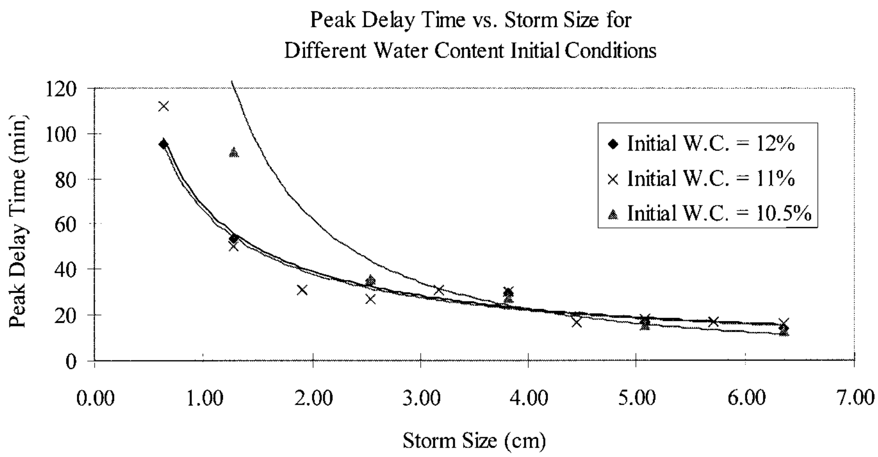

Fig. 16. Effects of initial conditions on peak delay time (24-h storms)

Table 5. Hydraulic Properties of Three Medias Simulated

Soil	θ_{sat}	θ_r	α	N	K_s (cm/s)	K_k (cm/s)	θ_k	Description
USDA Sand	0.42	0.02	0.14	1.59	0.006	0.006	0.42	Rawls et al. (1982)
Sand	0.40	0.07	0.07	3.00	0.05	0.026	0.25	Used in physical experiment
Gravel	0.40	0.03	0.20	4.41	1.00	1.00	0.40	Pipe bedding gravel

steady-state flow is reached before the peak input drops off, then no peak reduction will be observed. In order to determine the time required to reach steady state, simulations applying constant input rates were performed.

Constant Rate Application

Four constant rate rainfall simulations were performed to determine the effect of the input intensity on the time required to reach steady state and the total storage of the soil matrix. In general, the time to steady state decreased and the soil moisture storage increased with the corresponding increase in input intensity. Table 4 presents these results.

Referring back to Fig. 12, a peak highway runoff input intensity of 0.42 cm^3/s per unit length of ditch can be calculated from the 6.35 cm (2.5 in.) 24 h storm. This rate was maintained for a duration of approximately 60 min. Therefore, according to Table 4, steady-state conditions should have been met within 60 min. Fig. 13 illustrates the peak reduction for this storm was only 7%, which indicates near steady-state conditions were obtained.

Table 4 also provides support for the exponential decay trend of the percentage peak reduction with increasing storm size. Larger storm sizes are associated with higher intensities. Therefore, as storm size increases the storage in the soil matrix increases. This trend of increased storage tends to offset the drop in percent peak reduction as storm size increases. Once the system is entirely saturated, theoretically no peak reduction will occur since the storage capacity of the system is depleted.

A second important observation is the minimal impact on the peak delay time resulting from the two different distributions. The peak intensities for the two distributions are nearly the same as shown in Fig. 14, causing the same water content and corresponding hydraulic conductivity along the transmission path. Thus, input distribution shapes with the same peak intensity do not impact the minimum peak delay time. This indicates that the peak

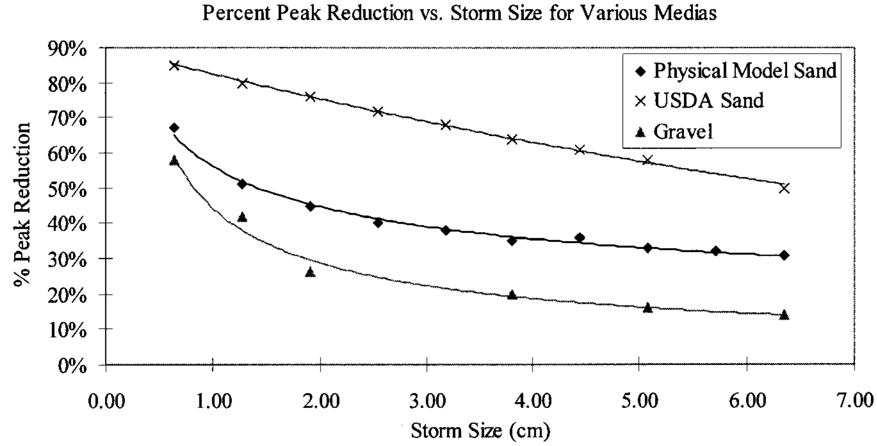

Fig. 17. Effects of different medias on peak reduction (24-h storms)

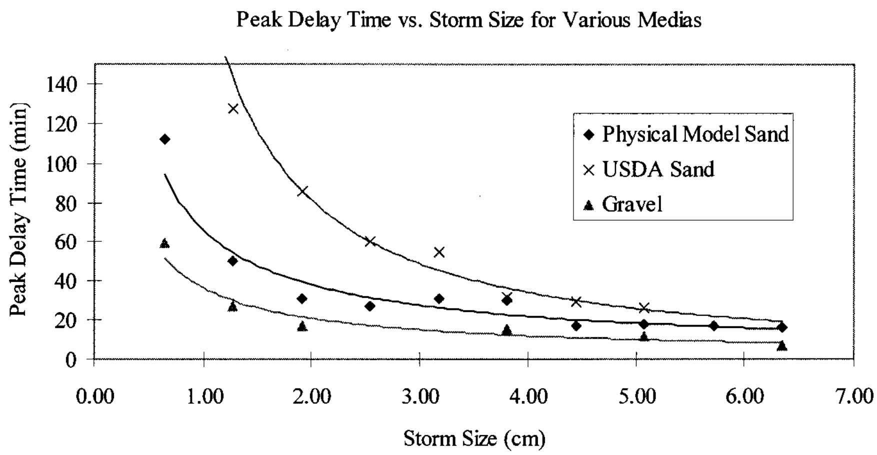

Fig. 18. Effects of different medias on peak delay (24-h storms)

flow occurs along a saturated flow path that is relatively unaffected by the excess water in the modified distribution. The excess water must be transmitted via a slightly thicker flow layer that does not significantly alter the peak flow path.

The following conclusions can be made regarding the effects of the input hydrograph distribution. First, the peak delay time is relatively unaffected by the input distribution. Second, the percent peak reduction is drastically affected by the duration of the peak input. This observation is analogous to a detention pond. Detention ponds treat short duration high-intensity hydrograph much better than a long lower-intensity hydrograph due to the available storage in the pond. A long steady rainfall depletes available storage reducing treatment efficiency. On the other hand, an empty pond may entirely consume a short, high-intensity rainfall event. The ecology ditch behaves in much the same way that leads to the impact of initial moisture conditions of the ditch media.

Effects of Initial Conditions

The impact of initial conditions on the ecology ditch's performance is important when considering the typical antecedent dry periods of an area. The hydraulic performance was tested under three different moisture contents in the sand layer. The driest initial condition was created based on 72 h between storms. Average water contents were approximately 10.5%. The initial condition used in nearly all of the experiments and simulations consisted of average water contents of 11% resulting from 24 h of drainage between storms. The wettest initial condition represented 3 h between storms with an average water content of 12%. As expected, the effect of initial conditions only impacted the hydraulic performance during smaller storms as shown in Figs. 15 and 16.

The hydraulic performance of the ditch for larger storms is not sacrificed or improved based on initial water content of the media. It is noted that the difference in initial water contents for each simulation is relatively small. However, recall the corresponding antecedent dry periods are 3, 24, and 72 h for the respective water contents of 12, 11, and 10.5%. These results show the minimum percent peak reduction and peak delay time should be relatively unaffected by moist initial conditions resulting from low-intensity rainfall patterns. On the other hand, initial conditions resulting from a week of hot summer weather is expected to have much greater and improved impacts on the hydraulic performance of the ditch.

Effects of Media

The effects of different ditch media on the hydraulic performance were simulated in the computer model. Gravel and USDA classified sand were compared to the sand used in the calibrated physical model (Rawls et al. 1992). Refer to Table 5 for the hydraulic properties of these media.

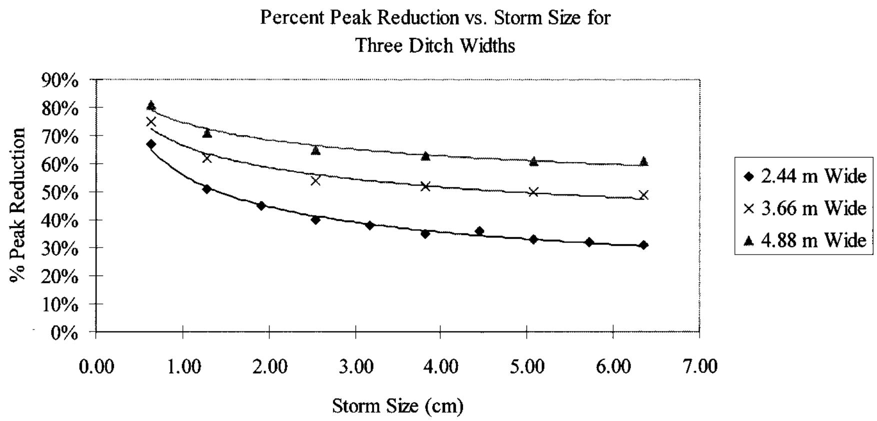

Fig. 19. Effects of ditch size on peak reduction (24-h storms)

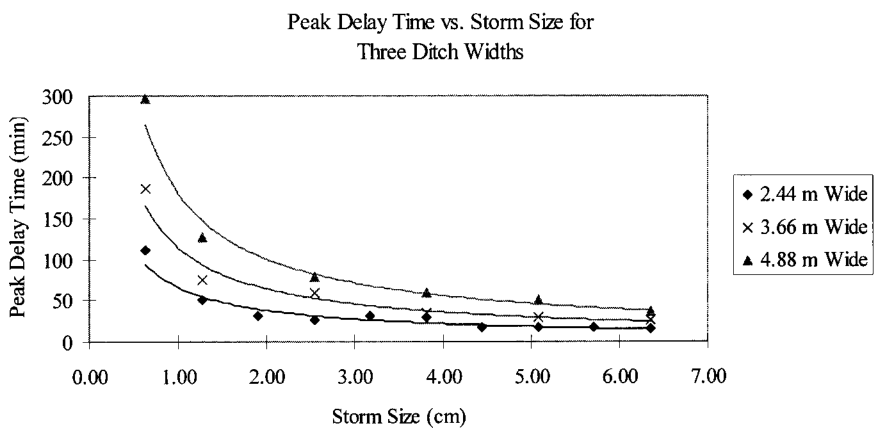

Fig. 20. Effects of ditch size on peak delay time (24-h storms)

The percent peak reduction is dependent on the storage characteristics of the media. Finer medias tend to retain water better causing larger percent peak reductions as shown in Fig. 17. Peak delay time is dependent on the effective hydraulic conductivity. Thus, finer soils having lower hydraulic conductivities produce greater peak delay as shown in Fig. 18.

Effects of Ditch Size and Side Slope

To test the hydraulic behavior of the ecology ditch as a function of size, three different geometries were tested. The primary difference between each size was in the width of the wings. Wing widths of 0.91 m (3 ft), 1.52 m (5 ft), and 2.13 m (7 ft) were tested and are referred to by total ditch widths of 2.44 m (8 ft), 3.66 m (12 ft), and 4.88 m (16 ft), respectively. All of these experiments were performed with the calibrated sand used in the physical model. In addition, the initial conditions resulted from 24 h of interevent drainage.

The hydraulic performance as a function of ditch size is very important in the design of the ecology ditch. Figs. 19 and 20 illustrate the impact of ditch size on the percent peak reduction and peak delay time, respectively.

A larger ecology ditch wing makes a substantial difference in the minimum values of the percent peak reduction. The minimum percent peak reduction for the 2.44 m (8 ft), 3.66 m (12 ft), and 4.88 m (16 ft) ditch sizes were 31, 49, and 61%, respectively. The reason for increased peak reduction is that the larger cross-sectional area of the sand layer provides greater storage capacity. The peak delay time is also affected by the increased size of the wings as shown in Fig. 20.

The peak delay time is increased with size due to longer transmission path lengths. The minimum delay times shown in Fig. 20 for the 2.44 m (8 ft), 3.66 m (12 ft), and 4.88 m (16 ft) ditch sizes were 16, 26, and 37 min, respectively.

Peak Delay Time Analysis

The hydrologic results show trends of exponential decay of both peak reduction and peak delay as a function of storm size. The impacts of different conditions, such as storm distribution, ditch media, and ditch size greatly impact the hydraulic performance of the ditch. Percent peak reduction is highly dependent on the unsaturated behavior of the soils and the input hydrograph distribution. Quantification of percent peak reduction for different conditions requires the use of a code such as *SWMS2D*. However, a fundamental trend was observed for peak delay time. Peak delay time can be estimated using a simple analysis.

An approximation for the minimum peak delay can be calculated provided that the following assumptions are valid: (1) the peak intensity of the input hydrograph is large enough to saturate the system; (2) once saturation has occurred, a unit gradient is assumed; and (3) the travel time through the pipe bedding gravel below the sand layer is assumed to be negligible since the hydraulic conductivity is an order of magnitude larger. Assumption (1) occurs in most large storm events. Based on the computer results, assumption (2) was true for the media tested in the physical model. This assumption, however, may not be valid for medias with drastically different hydraulic properties.

First of all, the seepage velocity (ν) is calculated using

$$\nu = \frac{q}{n} = \frac{K_s}{n} \tag{1}$$

where K_s=saturated hydraulic conductivity; and n=porosity. Next, the distance (D) along the transmission path is calculated by

$$D = t_{pd}\nu \tag{2}$$

where t_{pd}=user specified minimum peak delay time; and ν= seepage velocity from Eq. (1). After the distance along the transmission path is calculated, a ditch size can be formulated by assuming the transmission path closely represents the outside perimeter dimensions of the ditch.

This procedure for calculating peak delay time as a function of the seepage velocity and the distance traveled was proven by comparison to the results shown in Fig. 9. Recall these results correspond to the 2.44 m (8 ft) wide ditch with sand used in the physical model. The total length of the transmission path in the sand is approximately 127 cm along the liner. The porosity and saturated hydraulic conductivity are 0.40 and 0.05 cm/s, respectively. Assuming a unit gradient yields a maximum flux of 0.05 cm/s as given by Darcy's law, the seepage velocity is calculated at 0.125 cm/s by dividing the flux by the water content. The total travel time is approximated by dividing the transmission length by the seepage velocity. This set of calculations yields a minimum delay time of 17 min which corresponds very closely to the minimum peak delay times observed in the physical model experiment.

These calculation procedures are further tested using the experimental results for different ditch sizes. Applying the calculation of minimum peak delay time yielded good results for the different ditch sizes. Calculated delay times for 2.44 m (8 ft), 3.66 m (12 ft), and 4.88 m (16 ft) ditch sizes were 17, 26, and 33 min, respectively. The corresponding observed peak delay times for the three ditch sizes were 16, 26, and 37 min.

Conclusions and Recommendations

Based on the results of this research, the ecology ditch offers an effective means for the hydraulic treatment of storm water runoff. Using both a full-scale physical model and a modified two-dimensional unsaturated groundwater model, it has been determined that the percent peak reduction and the peak delay time followed exponential decay trends as a function of storm size. These values appeared to approach limiting values as the saturation level of the soil increased. Experimentation indicated peak reductions were dependent on the media used in the ecology ditch, the input hydrograph distribution, and the ditch size, while the peak delay time was dependent only on the media and ditch size. Also, the effects of initial conditions did not appear to have substantial impacts on either percent peak reduction or peak delay time for larger storms.

As demonstrated in Fig. 9, the effects of storm size on peak discharge and peak delay are substantial. For storm sizes ranging from 0.5 to 2.5 cm, the combined effects of the compost and sand in the ecology ditch retain enough water to reduce the magnitude of the peak discharge by approximately 70–50%. The immediate impact would be to reduce pipe size but the downstream impact might be to reduce scour. Furthermore, the timing of the peak is reduced anywhere from 15 to 60 min which could lead to longer time of concentrations.

The internal hydraulic processes of the ditch were found to be very complex because of the nature of unsaturated flow. In general, the level of peak reduction and peak delay time were highly dependent on the unsaturated properties of the soil. This was seen in the comparison of media types in which three relatively coarse materials behaved drastically different. Peak reduction was found to depend greatly on input hydrograph distribution and the ability of the soil to store water. In turn, the storage in the soil was found to be dependent on the intensities of the input hydrograph. The peak delay time for larger storms was quantifiable since it depended on the saturated hydraulic conductivity and the distance of the flow path.

Several important design recommendations can be made based on the results of this project. Based on simulations of different media types and laboratory results, sand and coarse gravel are the recommended medias for the upper soil layer and pipe bedding material, respectively. The sand should have similar hydraulic properties as the sand used in the physical model. Most importantly, the saturated hydraulic conductivity should fall within a range of 0.03 to 0.08 cm/s. There are two reasons for the tight range in hydraulic conductivity. First, if the material is any coarser, support of plant growth will be difficult in terms of water retention and an adequate media for root growth. Second, if the material is finer or the saturated hydraulic conductivity is less, clogging and ponding become an issue.

A coarse gravel is recommended in the trench around the pipe. The gravel used in the experiments was classified as 3/8 in. minus, which is a fine to medium gravel according to Yang (1996). In future applications, it is recommended that 5/8 in. minus or coarser material be used. Using a coarser gravel ensures water flow in the geometrically smaller area of the trench will not be restricted.

The side slopes of the wing walls did not have a substantial impact on the output hydrographs. However, it should not hurt the performance of the ditch to make the wing slopes shallower. If logistics in construction are easier with shallow side slopes, then slopes no smaller than 1:20 are recommended.

The ecology ditch also adds the potential for effective qualitative treatment. The level of sediment removal is expected to be high since it acts as a sand filter. In addition, there is potential for biological treatment of contaminants through plant growth. Further testing regarding the qualitative treatment capabilities is still needed. Field testing of the ecology ditch should be performed to examine impacts that were not easily tested in the laboratory. In particular, the long-term impact of aging and sedimentation accumulation on the compost layer and the effects of vegetation should be examined. Different types of compost should also be tested due to potential differences in hydraulic conductivities and adsorption characteristics.

Each BMP has its place as storm water controls. The engineer must optimize variables such as peak discharge, time of concentration, space, to arrive at an economically sound design. The ecology ditch is one more such BMP to put in the designers' toolbox.

Acknowledgments

The writers would like to thank the Washington State Department of Transportation for funding and support of this project. They would also like to extend their gratitude to Pat Syms for his assistance in designing and constructing the physical model.

References

Driscoll, E., Shelley, P. E., and Strecker, E. W. (1990). *Pollutant loadings and impacts from highway stormwater runoff, Volumes I–IV,* FHWA/RD-88-006-9, Federal Highway Administration, Woodward-Clyde Consultants, Oakland, Calif.

Duchene, M. McBean, E. A., and Thomson, N. R. (1994). ''Modeling of infiltration from trenches for storm-water control.'' *J. Water Resour. Plann. Manage. Div., Am. Soc. Civ. Eng.,* 120(3), 276–293.

Ellis, J. B., Harrop, D. O., and Revitt, D. M. (1986). ''Hydrological controls of pollutant removal from highway surfaces.'' *Water Res.,* 20(5), 589–595.

Federal Highway Administration (FHA). (1996). ''Evaluation and management of highway runoff water quality.'' *Pub. No. FHWA-PD-96-032*, U.S. Department of Transportation, Washington, D.C., June.

Fetter, C. W. (1994). *Applied hydrogeology*, 3rd Ed., Macmillan College Pub. Col., New York.

Harper, H. H., Yousef, Y. A., and Wanielista, M. P. (1984). ''Efficiency of roadside swales in removing heavy metals for highway associated nonpoint source runoff.'' *Am. Water Resour. Assoc.,* 20(1), 129–137.

Harrington, B. W. (1989). ''Design and construction of infiltration trenches.'' *Proc., Urban Runoff Water Quality Control,* ASCE, New York, 290–304.

Hewitt, C. N., and Rahed, M. B. (1992). ''Removal rates of selected pollutants in the runoff waters from a major rural highway.'' *Water Res.,* 26(3), 311–319.

Hillel, D. (1982). *Introduction to soil physics*, Academic, New York.

King, S. (1997). ''Hydraulic performance of the ecology ditch: A best management practice for the treatment of highway runoff.'' Master of Science thesis, Dept. of Civil and Environmental Engineering, Washington State Univ., Pullman, Wash.

Koob, T. L. and Barber, M. E. (1999). ''WSDOT BMP's for stormwater runoff in confined spaces.'' *Washington State Department of Transportation Research Rep. T9902-17*, Draft Final, Olympia, Wash.

Newberry, G. P., and Yonge, D. R. (1996). ''The retardation of heavy metals in stormwater runoff by highway grass strips.'' *Washington State Department of Transportation Research Rep., WA-RD 404.1*, Olympia, Wash.

Rawls, W. J. L., Ajuja, R., and Brakensiek, K. L. (1992). ''Estimating soil hydraulic properties from soil data.'' *Indirect methods for estimating the hydraulic properties of unsaturated soils,* van Genutchen et al., eds., Univ. of California, Riverside, Calif.

Schueler, T. R. (1987). ''Controlling urban runoff: A practical manual for planning and designing urban BMPs.'' *Dept. of Environmental Programs,* Metropolitan Washington Council of Governments, Washington, D.C.

Simunek, J., Vogel, T., and van Genutchen, M. Th. (1994). ''The SWMS_2D code for simulating water flow and solute transport in two-dimensional variably saturated media, version 1.2.'' *Research Rep. No. 132,* U.S. Salinity Laboratory Agricultural Research Service, U.S. Dept. of Agriculture, Riverside, Calif.

Urbonas, B., and Stahre, P. (1993). *Stormwater: Best management practices and detention for water quality, drainage and CSO management,* Prentice-Hall, Englewood Cliffs, N.J.

Wilson, G. V., Jardine, P. M., and Gwo, J. P. (1992). ''Modeling the hydraulic properties of a multiregion soil.'' *Soil Sci. Soc. Am. J.,* 56, 1731–1737.

Yang, C. T. (1996). *Sediment transport: Theory and practice*, McGraw-Hill, New York.